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Assessing the Relationship Between Environmental Lead Concentrations and Adult Blood Lead Levels

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This paper presents a model for predicting blood lead levels in adults who are exposed to elevated environmental levels of lead. The model assumes a baseline blood lead level based on average blood lead levels for adults described in two recent U.S. studies. The baseline blood lead level in adults arises primarily from exposure to lead in diet. Media-specific ingestion and absorption parameters are assessed for the adult population, and a biokinetic slope factor that relates uptake of lead into the body to blood lead levels is estimated. These parameters are applied to predict blood lead levels for adults exposed to a hypothetical site with elevated lead levels in soil, dust and air. Blood lead levels ranging from approximately 3–57 μg/dl are predicted, depending on the exposure scenarios and assumptions.

KEY WORDS: Blood lead; adult; exposure; model.

1. INTRODUCTION

In recent years, there has been significant interest in the potential human health risks resulting from exposures to lead in soil and dust. This concern is most often focused on young children because, given the same concentration of lead in soil and dust, children's exposures will be higher than those of adults. This is because of children's high hand-to-mouth behavior, and the amount of time they spend playing outside, coming into contact with and ingesting more lead-contaminated dirt. In addition, children absorb more lead ingested from soil and dust than adults absorb, and children are more sensitive to the toxic effects of lead.

However, adults may be exposed to high levels of lead in soil and dust in situations where there are no exposures to children. These situations include adults working on a daily basis in occupations that involve lead exposures, or adults involved in construction or remediation activities at lead-contaminated sites. In these situations adults may be at risk for elevated blood lead levels due to soil and dust exposures. For such situations it would be useful to have an adult lead exposure model to assess risk. It should also be noted that the United States Occupational Safety and Health Administration (OSHA) regulates lead in air in the working environment, but not lead in soil or dust,[1] further emphasizing the potential use of an adult lead exposure model.

An adult lead exposure model should relate lead concentrations in various media (air, water, soil, and dust) to blood lead levels. Several such models exist for assessing childhood exposures to lead, including the LEAD Model.[2] However, models designed to predict blood lead levels in children cannot be easily used for adults because of significant differences between children and adults in the pharmacokinetic parameters that control the distribution of lead in the body.

Models relating adult blood lead levels to some types of environmental exposures have been developed by O'Flaherty,[3] Carrington and Bolger,[4] and Chamberlain and Heard.[5] O'Flaherty predicted adult blood lead levels from exposure to air, water, and diet using a so-

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phisticated, multicompartment pharmacokinetic model. An individual's exposure history was developed from historic environmental lead levels and both steady and nonsteady state exposures can be modeled. Use of the model requires access to the computer program, and soil and dust exposures for adults are not considered. Carrington and Bolger predicted adult blood lead levels using a Monte Carlo analysis of estimates of the range of lead intake and lead concentrations in air, soil, dust, water, food, ceramics, and wine. They used an empirically derived conversion factor based on observations of blood lead values and dietary intake to relate lead intake to blood lead. The focus of their work was to predict the effects of lead in wine on blood lead levels of the adult population. Chamberlain and Heard modeled the overall lead balance for an individual based on several studies using lead tracers to track inhaled and ingested quantities of lead. They calculated total lead uptake from media-specific intake and clearance information, and related uptake to blood lead by comparing measured blood lead levels to uptakes estimated from their lead balance model. None of the models described provide a direct means of relating soil or dust lead concentrations to blood lead levels for adults with occupational exposures.

Here we propose a method to calculate adult blood lead levels that is based on statistical information concerning baseline exposures to lead arising largely from dietary lead and an assessment of current exposure to lead in soil, dust, water, and air. The estimated baseline exposure is applicable to adults with no large pre-existing burden of lead, or no previous excessive occupational exposures to lead. The value chosen to represent baseline exposures is summed with a calculation of current site-specific exposures based on standard relationships between lead concentrations, lead intake and uptake, and the relationship between lead uptake and blood lead in adults. Equations relating environmental sources of lead to blood lead levels rely on estimates for adults for several parameters, including the biokinetic slope factor (BSF) that relates blood lead levels to daily absorbed lead amounts, ingestion rates for soil and dust, water, an inhalation rate for air, and media-specific absorption fractions. The value for each of these parameters differs for adults and children.

In order to interpret the output of this model, it is necessary to describe the effects of lead on adults. The response of adults to lead is both quantitatively and qualitatively different from that of children.[6] For example, central nervous system effects, such as mood disturbance and psychomotor impairment, occur at lower blood lead levels in children than in adults, with effects from prenatal exposure occurring at somewhat lower levels than effects of postnatal exposure, (see, *e.g.*, results of prospective analyses in Boston, Refs. 7–9). Peripheral nervous system toxicity, such as wrist drop, is characteristic of high level lead poisoning in adults, but not in children. Thus one cannot simply extrapolate from results in children to evaluate risks of lead exposure in adults. We therefore describe health endpoints in adults to be considered in interpreting the output of a lead risk assessment.

Of particular relevance to assessing the impact of low level exposure to lead in adults are recent epidemiological studies demonstrating an association between blood lead levels and increases in systolic and diastolic blood pressure, as reviewed recently by Schwartz[10] and Weeden.[11] In general, there is a small, but significant, impact of lead on adult blood pressure (both systolic and diastolic). Schwartz observed that the impact of a 5 μg/dl difference in adult blood lead on diastolic blood pressure in males ranged from about 0.3–2 mmHg with an average of about 1 mmHg. Lead is one of multiple risk factors that affect blood pressure. For example, in a study by Rabinowitz *et al.*[12] on the effects of lead on hypertension in pregnancy, the correlation between blood lead and systolic blood pressure accounted for less than 1% of the variability in systolic pressure.

Although EPA has identified the impact of lead on blood pressure in adult men as one of the critical effects of low blood lead levels, EPA notes that a threshold for blood pressure effects in men has not been defined.[6] The strength and magnitude of the lead/hypertension association, as well as the relationship between increased blood pressure and risk of stroke or heart attack, should be considered in defining permissible blood lead levels for adults. Rather than propose a specific level, we present our analyses in terms of target blood lead levels defined by OSHA for adult workers and by the Centers for Disease Control (CDC) for young children.

OSHA states that the blood lead level of workers (male and female) intending to have children should remain below 30 μg/dl. OSHA allows 40 μg/dl as a "permissible" blood lead level in lead-exposed workers, below which no further medical monitoring or workplace intervention is required.

The Centers for Disease Control (CDC) has selected 10 μg/dl as the "level of concern" for young children. CDC concludes that when a "significant percentage" (undefined) of children in a community have blood lead levels between 10 and 14 μg/dl, some form of community intervention, such as educational programs, should be considered. While the CDC criteria for children were not developed for adults, they may be useful as a screening technique for adults. That is, if the predicted blood lead distribution would be considered acceptable for children, it would also be acceptable for adults.

In this paper, we provide estimates of blood lead levels for a group of adults with current occupational exposure at a hypothetical site that includes soil contamination and indoor dust contamination in a warehouse. Calculated percentages of workers with blood lead levels exceeding 10 μg/dl (the CDC screening criterion for children), 30 μg/dl (the OSHA nonmandatory criterion for adults intending to have children), and 40 μg/dl (OSHA permissible standards) are presented.

2. BASELINE ADULT BLOOD LEAD LEVELS

An estimate of baseline blood lead levels for adults without previous excessive occupational exposures can be obtained from the results of two recent epidemiological studies in Butte, Montana[13] and Midvale, Utah.[14] (Results from the soon-to-be released NHANES III study will provide a more comprehensive assessment of adult blood lead levels and could be used as input into the model.) These studies reported measured blood lead levels for 48 and 43 adults, respectively, with geometric mean blood lead levels of 3.1 μg/dl and 2.2 μg/dl, respectively. The measured range of blood lead levels in adults was from 0.5–12.0 μg/dl at Butte, and from nondetectable to 8.0 μg/dl at Midvale. These ranges can be described by geometric standard deviations (GSD) of 1.94 and 1.77, respectively. Because these levels are relatively low, we assume the adults in the studies had no significant previous occupational exposures to lead. The highest blood lead level of 12 μg/dl is much lower than the permissible adult levels under OSHA standards of 40 μg/dl. Adult blood lead calculations presented below use the higher geometric mean blood lead value from Butte, 3.1 μg/dl, as an average or baseline adult blood lead level in 1991 representative of adult exposures to average lead concentrations arising largely from lead in diet. It should be noted that use of a community-based baseline blood lead for the risk assessment model is, in fact, conservative, and likely to overestimate the actual value. The overestimate occurs because the proposed baseline for these individuals already incorporates some exposures from soil, dust, air, and water.

3. EXPOSURE MODELS

Multiple pathway exposure assessments depend on: (1) an evaluation of the concentration of the chemical of concern in each environmental medium; (2) a quantification of the variables affecting each potential exposure route, such as inhalation, ingestion, or dermal contact; and (3) an understanding of how daily exposure from each pathway is combined to represent a total exposure to the chemical from all sources and pathways. McKone and Daniels[15] have proposed a detailed multiple pathway exposure model that depends on each of these components, and that can be used for a variety of chemicals of concern. This model, and others like it, form the basis for the type of model presented here.

In the case of lead, total exposure is reflected in an individual's blood lead level, a variable that can be measured. A multiple pathway exposure model is used here to calculate adult blood lead levels that arise from environmental lead sources. The basic equation of the model is similar to that used in the U.S. EPA LEAD Model for children, but makes use of a biokinetic slope factor to relate total uptake of lead in adults to blood lead, rather than the multiple compartment distribution model for children used by the LEAD Model. (In theory, other modeling approaches such as structural equation modeling[14] could be developed for specific sites.) The following equation is used:

$$\mathrm{PbB} = \mathrm{PbB}_{\mathrm{baseline}} + (\mathrm{BSF})(\mathrm{Uptake}_{\mathrm{air}} + \mathrm{Uptake}_{\mathrm{water}} + \mathrm{Uptake}_{\mathrm{soil/dust}}) \tag{1}$$

where PbB stands for blood lead, $\mathrm{PbB}_{\mathrm{baseline}}$ refers to a baseline blood lead level which largely depends on dietary intake of lead, and BSF is the biokinetic slope factor that relates blood lead levels in μg/dl to daily absorbed amounts of lead in μg/day. The other source-specific uptakes (in μg/day) are defined by

$$\mathrm{Uptake}_{\mathrm{air}} = (A_a)(V_a)(C_a) \tag{2}$$

$$\mathrm{Uptake}_{\mathrm{water}} = (A_w)(I_w)(C_w) \tag{3}$$

$$\mathrm{Uptake}_{\mathrm{soil/dust}} = (A_{s/d})(I_{s/d})[(t_0)(C_s) + (t_i)(C_d)] \tag{4}$$

where A_a, A_w, and $A_{s/d}$ represent the absorption fractions for lead taken into the body from air, water, and soil/dust, respectively, V_a is the ventilation rate in m³/day, I_w is the ingestion rate of water in l/day, $I_{s/d}$ is the ingestion rate of soil and dust in g/day, and C_a, C_w, C_s, and C_d are the concentrations of lead in air (μg/m³), water (μg/l or ppb), and soil and dust (μg/g or ppm). The parameters t_0 and t_i refer to time-activity patterns that represent the relative proportions of soil and dust ingested, and sum to 1.

Concentration parameters are site-specific, while ingestion rates, absorption, and time-activity patterns may be similar for many sites. The calculated blood lead level is a geometric mean value representing an individual with average (or median) intake patterns. The expected range of blood lead levels for a group of workers or a community of individuals can be determined by applying an appropriate geometric standard deviation to the calculated blood lead value.

4. ASSESSMENT OF ADULT EXPOSURE PARAMETERS FOR ESTIMATION OF BLOOD LEAD LEVELS

In order to use the equations described in the section above, values for each of the parameters must be defined for adults. The following sections give the values used in this study. A summary of these values is given in Table I. The values given here may best be described as default values, and may be altered depending on specific site conditions.

4.1. Soil and Dust

Average soil and dust ingestion rates for adults have been estimated to be 0.02 g/day, approximately one fifth the average value for children.[2] Ingestion rates may exceed this value for especially dusty occupational settings. Absorption of lead from soil and dust is assumed to be 8% for adults, assuming the absorption from soil and dust is similar to absorption from food and water. A value of 8% may be an overestimate for soil and dust, based on the comparison of uptake of lead in soil and dust (30% as a maximum) vs. uptake of lead in food in children (approximately 50%[2]). It is likely that a lower absorption of lead from soil and dust than from food and water also occurs in adults. In addition, lower values for absorption from soil and dust may be appropriate for some communities (*e.g.*, mining sites[16,17]).

Table I. Adult Parameters for Current Exposure Blood Lead Calculations

Symbol	Description	Value
$A_{s/d}$	Soil/dust absorption	0.08
A_w	Water absorption	0.08
A_a	Lung deposition and absorption	0.32
$I_{s/d}$	Soil/dust ingestion	0.02 g/day
I_w	Water ingestion	2.0 l/day
V_a	Ventilation rate during waking hours	20.0 m³/day
BSF	Biokinetic slope factor	0.375 μg/dl per μg/day

4.2. Water

Adult water intake averages 2 l/day.[18] Absorption of lead from water for adults is estimated at 2–10% with meals and 40–60% between meals.[19] A recent article by O'Flaherty[3] suggests a value of 8% based on the literature and shows that this absorption works well in predicting adult blood lead levels from exposure to water and food.

4.3. Air

A detailed assessment of ventilation rates has recently been presented by Layton.[20] Layton suggests that the lifetime average inhalation rate for men is 14 m³/day (0.58 m³/hr) and for women is 10 m³/day (0.42 m³/hr). Information presented in Layton allows calculation of average daytime ventilation rates for adults aged 18–65. These values, averaged over all activities except sleep, are 20 m³/day (0.83 m³/hr) for men and 16 m³/day (0.67 m³/hr) for women. Calculations presented here use a ventilation rate of 20 m³/day, applied only to waking hours.

Absorption of lead into the blood stream from air taken into the lungs depends on the deposition rate of air lead in the lungs, and the absorption fraction of lead that is deposited. U.S. EPA[21] estimates that the range of air lead deposition is 28–70%, depending on particle size, ventilation rate, and type of work conditions. The absorbed fraction ranges widely, but an average value can be taken as 50%. This suggests that the amount of air lead in the lungs that is deposited and absorbed into the blood stream may range from 14–35%. This value is estimated at 32% for the following calculations. Site-specific information may suggest alternate values.

4.4. BSF

Biokinetic slope factors have not been directly measured for adults, but an estimate can be obtained from the work of Pocock *et al.*[22] who measured blood lead levels in over 7000 middle-aged men in 24 British towns. Tap water lead analyses were made at the residences of 941 of these men. This study found a relationship between blood lead levels and lead concentrations in residential tap water, and alcohol and tobacco consumption. Other sources of lead exposure, such as occupation, were not evaluated. Pocock and coworkers derived a slope of blood lead to water lead concentration of 0.[illegible] μg/dl blood lead per μg/l water concentration. An equation describing the contribution of water lead to blood lead can be derived from Eqs. (1) and (3) where

$$\mathrm{PbB}_{water} = (\mathrm{BSF})(A_w)(I_w)(C_w) \quad (5)$$

Rearrangement of this expression yields

$$\mathrm{PbB}_{water}/C_w = 0.06 = (\mathrm{BSF})(A_w)(I_w) \quad (6)$$

Substituting $A_w = 0.08$ and $I_w = 2$ l/day and solving for BSF yields a value for BSF of 0.375 μg/dl blood lead per μg/day lead uptake. A BSF value for children can be derived from the output of EPA's LEAD Model by dividing predicted blood lead levels by total uptake. The average value derived in this manner is about 0.3 μg/dl per μg/day, and compares favorably with the adult value used in this study.

5. ASSESSING POTENTIAL ADULT BLOOD LEAD LEVELS: A HYPOTHETICAL SITE

Calculations are presented here for a hypothetical site consisting of an industrial manufacturing warehouse with substantial interior dust lead contamination, elevated air lead concentrations, and surrounding acreage containing waste dumps of lead-containing material that has contaminated the soil. Table II summarizes hypothetical geometric mean concentration levels for soil, dust, and air that are used for the following calculations. The background level of lead in soil and dust used in the following calculations is approximately the natural level of lead in soil in many parts of the United States. The background level of lead in air is taken from the LEAD Model default value for the average concentration of lead in air.

Two exposure scenarios are considered: the outdoor worker, who spends all of his working time outdoors on the site, and the warehouse worker, who spends all of his working time inside the warehouse. A geometric mean blood lead level is calculated from the following relationship:

$$\mathrm{PbB} = 3.1 + (\mathrm{BSF})[(I_{s/d})(A_{s/d})(t_s)(C_{s/d} - C_{bgs/d}) + (V_a)(A_a)(t_{s2})(C_a - C_{bga})] \quad (7)$$

where t_s and t_{s2} represent time-activity patterns corresponding to the fraction of waking hours spent on site (for assessment of onsite percent of soil and dust ingestion), and the fraction of total hours spent on site (for assessment of onsite percent of ventilated air), respectively. (Soil and dust ingestion occurs only during working hours, assumed to be 16 hr/day, while air inhalation occurs 24 hr/day.) We assume that the workers spend 8 hr/day, 5 days/weeks, 50 weeks/year onsite. Values of t_s and t_{s2} are therefore 0.34 and 0.23, respectively. Background concentrations of lead in soil/dust and air are subtracted from the site concentrations because time spent onsite replaces exposure that would otherwise be to background lead levels. No elevated exposures to lead in water are considered for this hypothetical site.

Solving Eq. (7) with the values of the parameters given in Tables I and II yields a geometric mean blood lead for the outdoor worker of 3.4 μg/dl and for the warehouse worker of 6.8 μg/dl.

We describe the hypothetical industrial manufacturing warehouse as a dusty place with significant particulate matter in the air due to the nature of the work. We therefore assume that the working adult in such an environment may ingest more soil and dust than they might otherwise in, for example, a residential environment. An alternate calculation of the warehouse worker blood lead level can be made by assuming that during the time the adult is in the warehouse his soil and dust ingestion rate increases to 0.1 g/day, or 5 times the value used in the previous calculation. This higher assumed ingestion rate results in a geometric mean blood lead level for the warehouse worker of 19.8 μg/dl.

A range of blood lead levels consistent with these exposure conditions can be estimated by applying an appropriate blood lead GSD value to the calculated geometric mean blood lead. Observed GSDs for adults at Butte and Midvale were 1.94 and 1.77, respectively. EPA's Draft Lead Guidance Manual suggests that the range of blood lead levels for a population with a narrow range of exposure conditions, such as a group of children all living in one house, may be described by a GSD of approximately 1.35. More accurate estimates of the blood lead GSD in adults will be available from the NHANES III study. For a potential maximum adult blood lead for workers exposed to this site, we assess the 95th percentile blood lead level using GSD values of both 1.4 and 1.9.

Table II. Lead Concentration Levels for the Hypothetical Site

Symbol	Description	Value (geometric mean)
C_s	Soil concentration	1450 ppm
C_d	Dust concentration in warehouse	16,000 ppm
C_a	Air concentration in warehouse	1.0 μg/m³
$C_{bgs/d}$	Background concentration of soil and dust	100 ppm
C_{bga}	Background concentration of air	0.20 μg/m³

Table III. Summary of Predicted Blood Lead Levels

Scenario	Outdoor worker		Warehouse worker low ingestion rate		Warehouse worker high ingestion rate	
Geometric mean (μg/dl)	3.4		6.8		19.8	
GSD	1.4	1.9	1.4	1.9	1.4	1.9
95[th] percentile (μg/dl)	5.9	9.8	11.8	19.5	34.4	56.9
% > 10 μg/dl	0.07	4.6	12.6	27.4	97.7	85.6
% > 30 μg/dl	< 0.01	0.03	< 0.01	1.0	10.8	25.9
% > 40 μg/dl	< 0.01	0.01	< 0.01	0.29	1.8	13.7

The resulting values are 5.9–9.8 μg/dl for the outdoor worker, 11.8–19.5 μg/dl for the warehouse worker with the low soil/dust ingestion value, and 34.4–56.9 μg/dl for the warehouse worker with the high soil/dust ingestion value. A summary of calculated geometric mean blood lead levels together with the 95th percentile and percentages of workers predicted to have blood lead levels exceeding 10, 30, and 40 μg/dl for these scenarios is presented in Table III. It is clear that the maximum blood lead values are very dependent on the choice of GSD. Higher GSD values will increase the percent of workers with high blood lead levels and lower GSD values will decrease the percent. In addition, blood lead levels greater than about 20–25 μg/dl are likely to be overestimates due to nonlinearities in the relationship between lead exposure and blood lead (see, e.g., Fig. 2 of Pocock *et al.*, Ref. 22). Nevertheless, these calculations give some qualitative indication of the range of blood lead levels that might be expected from adult exposure to this hypothetical site.

6. SUMMARY

We have presented here a preliminary model to assess adult blood lead levels arising from site-specific exposures to elevated lead levels in air, water, soil, and dust. An example for a hypothetical site with substantial dust lead contamination in an industrial manufacturing warehouse shows that the blood lead levels may range from an average expected value of 6.8 μg/dl to a potential 95th percentile value as high as 57 μg/dl for warehouse workers. The outdoor worker may have an average expected blood lead value of 3.4 μg/dl with a 95th percentile estimate between 6 and 10 μg/dl. The example shown here includes a calculated increment to blood lead due to exposure to elevated air, soil, and dust lead levels. Although no example is provided for water, the method is formulated to include any medium, and adult exposures to elevated water lead concentrations can be similarly assessed.

We believe this model will be useful in identifying the most important sources of lead exposure in adults and in assessing the potential impacts of anticipated future lead exposures. Information developed from this model may be applied to risk management activities aimed at adult lead exposures. It should be emphasized that we have presented a model with default parameters. These parameters should be modified based on site-specific information. Paired environmental and blood lead data would be useful in assessing these model parameters for adults. In such a situation, the influence of prior lead exposures would be particularly important to evaluate.

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